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THE IMPORTANCE OF FLUVIAL MORPHOLOGY IN HYDRAULIC ENGINEERING

E. W. Lane,* M. ASCE

Morphology may be defined as "the science of structure or form" and fluvial may be defined as "produced by the action of flowing water." Since rivers can hardly be said to have structure, fluvial morphology is therefore the science of the form as produced by the action of flowing water. It is a branch of geomorphology, the science of the form of the earth's surface. Geomorphology has also been called physiography.

Fluvial morphology is particularly important to the hydraulic engineer because many of his greatest problems arise because of the form of streams brought about by the transportation and deposition of sediment by them. For the proper solution of these problems, a knowledge of the principles of fluvial morphology is often necessary. Among the problems in which fluvial morphology is a very important factor are many of those dealing with water resources development and include some of the most important river problems in the world. Among these are flood control on the Lower Mississippi and on the Lower Colorado Rivers (of California and Arizona), the development of the hydraulic resources of the Missouri and Arkansas Rivers in the United States, the Yellow and Huai River flood problems in China, the Kosi River floods in India, and many others. As streams become more highly developed, and changes in sediment movement due to stream developments slowly become evident, the importance of the morphological aspect of river control problems will be increasingly appreciated.

Early History

The science of fluvial morphology has developed from two roots which have been largely independent of each other. The most vigorous root is in the science of geomorphology where the principal originators were the geologists, J. W. Powell,(1) G. K. Gilbert,(2) and W. M. Davis,(3) who worked in the latter part of the past century and early part of the present one. The work of these men dealt chiefly with the form of the surface of the earth and the importance of flowing water in causing the present shape, but Gilbert also made extensive investigations into the quantitative aspects of sediment transportation. The other root is in engineering and goes back much further, to Dominique Guglielmini,(4) about 1697, who was probably the first writer on fluvial morphology. As early as 1750,(5) engineers were arguing about the advantages and disadvantages, from the standpoint of navigation, of dividing the Rhine into several channels and were constructing hydraulic models to prove their contentions. Very complete histories of the developments of this science in the field of engineering can be found in the summaries of Hooker(6) and Mavis.(7) Unfortunately for both engineering and geology, these two roots, except for the work of Gilbert, have remained largely separate down to the

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present time; but it seems probable that in the future a closer coordination of the two fields will exist to the advantage of both.

Nomenclature of the Geomorphologists

One of the best contributions made by the geomorphologists to the science of fluvial morphology is the nomenclature which they have introduced. Rivers have been classified by them on two bases: 1) on the basis of the method of formation, i.e., whether the position of the river is as a consequence of the initial slope of the land area or as a result of other factors[8, p. 171] and 2) on the basis of the stage which has been reached in the development of the stream. From the standpoint of the approach of this paper, the first of these methods of classification has little usefulness; but classification on the basis of stage of development introduces ideas of major value. A number of the morphologist's descriptive terms for rivers, such as meandering and braided, have been generally adopted. The conception of "base level" and of a "graded river" are also very useful, as are also the terms "agrading" for the change of the level of a river whose bed is rising and "degrading" for change downward.

The Geomorphological Approach

As previously mentioned, the geomorphologist is interested in fluvial morphology principally as a tool in explaining the origin of the present form of the surface of the earth. The science appears to be of comparatively recent origin. Although many able men contributed to its early development, the outstanding work is that of W. M. Davis.[3] According to the Davis conception, the primary action in the formation of the earth by moving water is the geographical or geomorphic cycle which is a cycle of erosion passing through several stages. It starts with a nearly flat land surface which is gradually warped by movements of the earth's crust. This gives rise to increased erosive and transporting power of the water flowing from the land, the water beginning to carve the landscape into various forms. As time goes on, the forms of the land surface change, the various types of topography being characteristic of the various length of time during which the water has acted. Material is constantly being carried away from the land surface and deposited (usually in the sea); and the elevation of the land surface is gradually lowered and flattened until, after a very long period of time, the end of the cycle is reached when the whole surface has been reduced to a very gently sloping plain called a peneplain, and thus comes back to the condition in which the cycle started.

The various types of topography in the cycle were designated by Davis in terms of the stage reached in this cycle, using a terminology commonly adapted for designation of the age of a man. The stages began at the start of the cycle with youth, which passes into maturity and then into old age. The topographic forms typical of the first stage are spoken of as young or youthful, later ones as mature, and those of the last stage as old, with further subdivisions when desirable such as, for example, early and late maturity. The same set of terms are used to designate the stage of development of streams, and certain characteristics are typical of rivers of these various stages. Davis' designation by means of terms of age is somewhat confusing, as a mature stream may later become a youthful one. Also, although the stage reached by the stream usually corresponds with that of the surrounding

topography, this is not necessarily the case. An entire river need not be at the same stage throughout; usually a stream is less youthful in character near the mouth than in the vicinity of its headwaters.

Fluvial morphology as developed by the geomorphologists is largely a qualitative or descriptive science and suffers somewhat from a lack of quantitative relations, but many keen minds have contributed to it. It is not the intention in this paper to present in detail the geomorphological approach to this subject but rather to present geomorphology from an engineering viewpoint in order that the engineer may have the advantage of the extensive work of the geomorphologist, and that the latter may possibly gain something from the engineering viewpoint. An engineer who wishes to become a specialist in this field of fluvial morphology should thoroughly study numerous books and original sources of this part of the sciences.[8, 24, 25, 26, 33, to 37 inc.]

Characteristics of the Various Stages of Development of Rivers

In the same way that a person rapidly forms an opinion of the age of another person from the presence or absence of certain features which are characteristic of the various ages, a geomorphologist forms his opinion of the stage of development of a river from the presence or absence of certain conditions which are characteristic of the various river stages. According to the classical conception, young rivers are characterized by their ability to cut their stream beds downward with, geologically speaking, considerable rapidity; and the characteristic features are those which result from this action. The valleys of young streams are usually V-shaped or are deep gorges or canyons. Waterfalls or rapids often exist in these streams because sufficient time has not passed since they were uplifted for the stream to cut down and thus eliminate them. There are frequent changes of the grade of the stream caused by the hardness of the strata over which the stream flows, and pot holes are sometimes found. Because the valleys are steep sided and narrow, there is very little flat land in their bottoms; and highway and railroad construction along them is accomplished with difficulty. Douglas Johnson[26] suggests that early youth ends when lakes are eliminated, and middle youth ends when falls and rapids are eliminated.

Late youth ends and early maturity begins in a stream when the stream ceases to cut down rapidly but continues to widen out the bottom of the valley. This occurs in any stretch of the river when the sediment supplied by the river upstream, the tributaries within the stretch, and the erosion of the banks and valley sides is equal to the transportation capacity of the river. It then ceases its rapid cutting down, but the valley widens out as the material from the banks and valley sides continues to be carried away. Normally, the river would continue to lower its bed as the whole drainage area is lowered; but this is a very much slower rate than the lowering in a youthful stream. Early maturity ends and late maturity begins when the valley width equals the width of the belt covered by meanders of the stream. Late maturity ends and early old age begins when the valley width reaches several times the meander belt width.

The features usually associated with maturity in streams are flood plains, no rapids or falls; and meanders with oxbow lakes, but no other kinds of lakes. There are no sharp divisions between the various stages, nor is there general agreement as to when the various stages end. For example, an old river is sometimes considered to be one in which all of whose tributaries have reached maturity. Also some consider that when the flood plain widens

to the width occupied by the stream's meanders, so that these can move unrestrained by the valley walls, the end of the maturity stage is reached; and when the flood plain is wider than this, the river is old. These limits differ from those previously stated.

The foregoing classification represents the views of the classical or Davis school of geomorphologists; but a questioning of it has recently arisen, largely among those dealing with the Lower Mississippi River, who believe that the classical viewpoint puts too much emphasis on erosion and the formation of erosional peneplains and not enough on the depositional aspects. According to their view, the Lower Mississippi River with its meanders, oxbow lakes, and natural levees, and with a flood plain several times the meander belt width is still a comparatively young stream since it is building up the land along its course. There seems to be some justification for this new viewpoint. Obviously when an uplift occurs and streams start to cut down, there must soon be a part of their length, even though a relatively short one, along which at least part of the eroded material is deposited. This part of the stream is thus building up, and this process is as characteristic of a stream in the early part of the geographic cycle as is the cutting down of the high lands. It will thus be seen that the classical classification of age of a stream may be inexactly related to chronological age and that there is room for further work in classification to bring about a more logical system.

Base Level

Another of the concepts of the geomorphologist which is very useful to the engineer is that of base level. If the quantity of water in the ocean remained the same and no moving of the earth's crust took place, the dry surface of the earth would eventually be reduced nearly to sea level. Sea level is thus the ultimate base level toward which all streams tend to cut their beds. There are often certain local levels which, geologically speaking, temporarily are elevations toward which streams tend to cut their beds. Lakes, for example, for the period of their existence, control the level of streams entering them and thus form local or temporary base levels for such streams. Waterfalls and rapids often form local base levels. The bed of a large stream usually forms the temporary base level for its tributaries. There are here also borderline cases where it is difficult to establish the existence of a local or temporary base level, but usually they are quite evident.

Equilibrium in Natural Streams

The concept of equilibrium in streams as developed by the geomorphologist is also a very useful one to engineers. This concept is not unknown to engineers, but it has been more actively studied by geomorphologists. A variety of terminology has been used to express this condition. A stream in equilibrium is said to be a graded stream, a poised or balanced stream, or to be a regime stream or a stream in regime. Makin[25 p. 471] has given the following definition:

> "A graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium."

When a stream is capable of carrying more sediment than is supplied to it,

it carries away material from its bed and thus tends to lower the bed. This cutting down increases the slope of the tributary streams which causes them to bring down more material to the main stream. The more the stream cuts down into the surrounding land, the greater becomes the load supplied to it. Since most streams eventually reach either the ocean or some other base level as they cut down their beds, their slopes decrease; and, therefore, their ability to carry away the sediment brought to them is diminished. With the amount of material brought down to the stream increasing and the stream's ability to carry it away decreasing, a point is eventually reached where the rate at which sediment is brought to the stream becomes substantially equal to the rate at which it is carried away by the stream and a condition of equilibrium is reached. Under these conditions the bed neither cuts down nor fills up.

Ordinarily in natural streams the flow of water is not constant but continually varies, the ratio of the high flows frequently being a hundred or more times the low flows. Although the stream tends to pick up or deposit the bed material until its load equals its capacity to transport the load, because of the rapid variations of flow and sediment supply, a condition of equilibrium in which the load exactly equals the capacity of the stream to transport rarely exists except momentarily. Since the tendency of streams is to wear the land surface down to sea level and hence to lower their beds, considering a very long period, geologically speaking, the tendency is for more sediment to be removed from a section of a stream than is supplied to it; and, therefore, when long periods are considered, natural streams are rarely in equilibrium. Normally, therefore, neither in very short or very long periods may natural streams be considered to be in equilibrium.

Over long periods, historically speaking, however, it is true that the beds of a large number of streams, for most practical engineering purposes, are substantially in equilibrium; and accurate conclusions for many purposes may be reached by assuming equilibrium to exist. In some streams the bed may be slightly lowered in floods but fill back to their former level as the flood recedes and, except during floods, be at practically the same elevation even at the end of a long period of years as at the beginning of it. Although exact equilibrium is only momentarily obtained and, geologically speaking, a stream may be slowly degrading or agrading, for practical purposes it may be considered to be in equilibrium. The term equilibrium in this case may be likened to the term sea level, which for practical purposes is considered to be a fixed level, although the surface of the sea is constantly fluctuating above and below this level due to waves and tides; and, over very long periods of time, the sea level may rise or fall scores of feet due to more or less water being stored on the land surface in the form of glaciers.

For engineering purposes a section of a stream may, therefore, be said to be in equilibrium if, although it may continually fluctuate between aggradation and degradation, over a long period of years, in terms of human history, the net amount of change is not sufficiently large to be detected by quantitative measurements. It is believed that most alluvial streams, where not affected by the works of men, may thus be said to be in this equilibrium or graded condition.

If equilibrium exists in a reach of a river, a change of only one condition at a single point which would upset the equilibrium at this point would, if no other factors changed, eventually upset the conditions of equilibrium throughout the entire reach and bring about a new condition of equilibrium in this reach. Except in short reaches, however, other changes probably occur

before the readjustment to any one change is complete; and in most streams on which man has built hydraulic works, several changes are going on at the same time. Not infrequently, however, one change is so large compared with the others that it overshadows the minor ones and appears as a single change.

Changes of the Profile of Natural Streams

As the science of sediment transportation and deposition develops, it will be possible to predict more and more closely the morphological changes which will take place in a river due to any set of conditions and the rate at which they will occur. In the future the necessity of making such predictions is likely to increase. Such quantitative predictions can often be made by means of the knowledge of sediment transportation now available if all of the factors are known with sufficient accuracy. Usually, however, the data is not sufficient for quantitative estimates; and only qualitative estimates are possible.

The following very general expression will be found useful in analyzing qualitatively many problems of stream morphology:

$$Q_s \, d \sim Q_w S$$

Here Q_s is the quantity of sediment, d is the particle diameter or size of the sediment, Q_w is the water discharge, and S is the slope of the stream. This is an equation of equilibrium and if any of the four variables is altered, it indicates the changes which are necessary in one or more of the others to restore equilibrium. For example, if a stream with its sediment load is flowing in a condition of equilibrium and its sediment load is decreased, equilibrium can be restored if the water discharge or the slope are decreased sufficiently or if the diameter of the sediment is increased the proper amount. This equation is not an exact mathematical equation as it will not give the quantitative values of the variables involved which bring about equilibrium, but it is helpful to indicate qualitatively the changes which will take place in a stream when a change of any one of the variables occurs.

The sediment discharge, Q_s, in this equation is the coarser part of the sediment load or more exactly the bed material load,* since this is the part of the load which largely molds the bed formation. In most cases, the quantity of the fine load of silt and clay sizes can change almost indefinitely without materially affecting the river profile. In the following discussions of profile changes, changes of sediment load will be considered to mean changes of bed material load.

Classes of Stream Profile Changes

The changes which take place in the profile of a graded stream in equilibrium, due to a change of one or more of the factors controlling equilibrium, usually fall into one of six classes. One of the most common classes (Class 1) is the change that takes place in a stream with an equilibrium Grade BA as shown on Figure 1-a which reaches a base level at A, due to a change of conditions in the channel. Suppose the change of conditions is an increase in the sediment load Q_s beginning at C without changing the size of the sediment diameter d or the water discharge Q. To re-establish equilibrium the slope

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*Bed material load is sediment in transport of sizes readily available in considerable quantities in the stream bed.

S must be increased. Ordinarily after such a change of conditions a new equilibrium tends gradually to be established as follows: When the change of condition first occurs the stream between C and A cannot carry the increased load of sediment, and some of it is deposited on the bed downstream from C causing the bed to rise or aggrade to C'. At first this deposit may not extend down to base level but may end at E. As the deposit continues, the bed level may be increased to C'' , and the rise or aggradation may extend all the way to A. If the new condition continued a long enough time, a new equilibrium Grade C''' A would eventually be established; and no further rise or aggradation in the grade would take place.

The same changes would take place if instead of the sediment discharge Q_s increasing at C, the size of the sediment d was increased at C, leaving the sediment discharge Q_s and water discharge Q the same. A decrease of the water discharge Q leaving Q_s and d the same would produce the same result.

The foregoing changes also would cause a change of grade above the point C. The raising of the bed to C' would cause a decrease in the slope S upstream from the point C. The stream could not transport the sediment brought down on this flattened slope; and some of it would be deposited upstream from C, aggrading the stream bed upstream from C. As the stream bed below C aggraded, that above would also rise, approaching a final equilibrium Grade C''' B''' parallel to the original equilibrium Grade CB. The height of C''' B''' above CB would depend on the magnitude of the change of conditions which brought it about. The raising of the grade of the main stream in this way would also usually cause a rise in the grade of the tributaries entering the raised section, extending up the tributary a greater or less distance depending on the conditions in its bed.

Examples of Class 1

One of the common causes of a change in stream profile as in Class 1 is the decreasing of Q by taking the water out of the stream for irrigation, desilting the water, and returning the sediment to the river again, thus decreasing Q without changing Q_s or d. In the Rio Grande and in the Arkansas River in the United States, this has resulted in a rise in level of the river bed which causes many difficulties. A rise of the Yuba river bed in northern California, U.S.A., of about 20 feet started about 1850 due to the increase in the sediment load Q_s resulting from the discharge into the streams of large quantities of gravel wasted in the hydraulic mining of gold.(22) After hydraulic mining activity was greatly reduced, the height of this deposit gradually decreased, tending to restore the former levels. A similar case is the Serendah River in Malaya, where the river bed rose 21 feet in the years 1922-1933 due to the addition of sediment from the hydraulic mining of tin.(32) A very striking example is the Mu Kwa River in Formosa, the bed of which raised about 40 feet in 3 years due to the addition of sediment to the river from landslides. A two-story hydroelectric powerhouse along the side of the river was completely buried (Figure 2).

A rise of the stream bed may also occur due to the increase in sediment load brought into the stream by a tributary. The slope of the Missouri River for some distance upstream for the mouth of the Platte River is flatter; and below the mouth it is steeper than the slope of the remainder of the river in this vicinity, which is said to be due to the large quantity of coarse sediment brought in by the Platte River. The deposits brought in by a tributary may cause the stream bed downstream from the mouth of the tributary to build up so rapidly that the deposit upstream may not be rapid enough to keep the bed level upstream higher than that downstream. The deposits downstream then

form a sort of dam which causes a lake to form upstream from the tributary mouth. An example of this condition is found at Lake Pepin which has been formed in the Upper Mississippi River by the great load of sand brought into it by the Chippewa River. Matthes reports that the sediment brought down the Yuba River previously mentioned temporarily formed a dam in the Feather River, into which the Yuba discharged, which caused a lake 10 miles or more long; and later the sediment coming down the Feather River formed another temporary dam in the Sacramento River, into which the Feather River discharged, which also produced a lake. Farther down the Sacramento River at the city of Sacramento, California, U.S.A., the low water stage was raised 10-1/2 feet by the deposits. This maximum stage was reached in 1890. The discharge of gravel into the streams was prohibited by law and the deposits decreased, restoring the original stage at Sacramento by 1920.

Examples of Class 2

Class 2 is similar to Class 1 but results in a lowering or degrading of the profile of the stream due to a decrease in the sediment load or its particle size or an increase in the water discharge. A reduction of the sediment load Q_s of the stream at point C (Figure 1-b) is brought into balance by a reduction of slope S from point C to the base level at A and upstream from C the bottom is lowered but retains the same slope as before. In this case, tributaries entering the stream usually have their beds lowered also.

A very common cause of such a lowering is the abstraction of part or all of the sediment load from a stream by the deposit of it in the quiet water upstream from a dam. Downstream from the dam the river bed is often considerably degraded because of the sediment carried away from the bed by the clarified water. This action caused the failure of an important dam in India. Many other changes of Class 2 have been observed on the Indus River.[29,30,31] A stream profile change of Class 2 necessitated the complete reconstruction of Fort Sumner Dam on the Pecos River in New Mexico. The extent of the degradation below this dam is shown in Figure 3. Stream profile changes of Class 2 have affected in some cases beneficially and other cases detrimentally a large number of water power plants. A knowledge of the magnitude of this action is an important factor in the design of the spillways of many dams, since failure to correctly estimate the lowering may in some cases cause failure of the spillway or even of the dam itself. A number of cases of degradation below dams have been described in technical literature.[13,27]

The increase of the flow Q_w has the same effect as a lowering of the quantity of sediment Q_s. A very striking case of stream bed lowering due to an increase in the flow has occurred in Five Mile Creek in Wyoming, U.S.A. The added flow is due to the waste water of an irrigation project constructed in the valley of this stream. Here the stream bed has degraded until it has uncovered rock ledges which were below bed level and produced waterfalls and rapids where the water flows over these ledges as shown in Figure 4. This degradation removed about 1,000 acre feet of sediment in a year from the stream bed and banks and which is depositing in and rapidly filling a reservoir a short distance downstream.

An interesting example of stream bed lowering due to a reduction of the quantity of sediment Q_s has occurred in Cherry Creek in Denver, Colorado. Large quantities of sand have been removed from the stream for building construction; and downstream from the point of removal, the bed degradation has extended to the mouth, a distance of about 5 miles. Figure 5 shows the magnitude of the lowering which took place at one point in about 2 years. The construction of a number of check dams was necessitated to hold up the bed

level and prevent the undermining of walls, bridges, and sewers along this creek. A similar degrading has resulted on the Loup River near Bolus, Nebraska. A canal for hydroelectric power was constructed from one branch of the stream to a power plant on another branch. The increased flow in the branch below the power plant caused a lowering of the grade of the river above the plant and extended downstream 1-1/2 miles to the junction of the two streams below which the discharge is unchanged. The effect was beneficial to the power development as it increased the fall available for producing power by about 5 feet, but it caused damage to the foundations of bridges over this portion of the stream.

Usually the changes involved go on quite slowly but under certain conditions changes of surprising magnitude and rapidity can take place. Todd and Eliasson[11 p. 376] report that in a 30-mile stretch in the Yellow River, the bed was deepened an average of 15 feet. At Lungmen the bed was lowered approximately 30 feet over a width of 3,000 feet, the depth tapering off upstream and downstream removing an estimated quantity of 9,000,000 cubic yards in not more than 12 hours. The cause of this phenomenon is not indicated; but it was probably due to an increase in discharge, perhaps of less heavily sediment laden water.

Examples of Class 3

Class 3 changes of stream bed profile are those which occur when the grade of the stream is suddenly raised at one point. The most common cause of such a rise is the construction of a dam; but such changes also occur from natural causes, such as the damming of rivers by landslides, mud flows, lava flows, or the advance of a glacier. This class is represented by Figure 1-c which shows the changes which occur in the bed of a stream in equilibrium when the grade at one point is suddenly raised.

If the stream grade is raised suddenly enough, a lake is formed upstream from the point of rise; and this lake is then gradually filled with sediment brought down by the stream. The conditions during the filling period are represented by the profile ending at C' on Figure 1-c. The unusual shape of the stream profile is due to the coarse sediment being deposited at the upper end of the reservoir and the fine material being carried farther into the lake or flowing down the lake bottom as a density current. The reservoir is filled when the stream bottom is raised to point C", and part of the sediment load passes over the obstruction. The grade continues to rise upstream from the dam and approaches a final equilibrium grade which is parallel to that before the grade was raised. This was probably first pointed out by Harris[28] over a half century ago. The changes discussed under Class 1, where lakes were formed upstream from the tributaries, are also occurrences of Class 3.

The length of the lake filling stage in this class depends largely on the volume of the lake and the rate at which sediment is brought down by the stream. When the reservoir volume is small and the rate at which sediment is brought down is great, the length of the filling period is short and the effects upstream from the lake may develop very rapidly. For example, the deposits above the Imperial Dam on the Lower Colorado River within 7 years were causing a rise of the stream bed 55 miles upstream from the dam, whereas the level pool above the dam originally extended only 15 miles upstream. The profile of the river upstream from the dam had already reached a gradient of three-fourths that of the original slope which was probably very close to the equilibrium grade. The bed 55 miles upstream would have continued to rise and the effect would have extended much farther upstream had it not been for the degradation effect, as discussed under Class 2, from

another dam built farther upstream about the same time.

Another interesting example of similar action was observed on the Nanshik-chi River in Formosa. This stream had a slope of about 1:120. A dam about 13 meters high was constructed on this stream 1.3 km below a hydroelectric power plant. In 7-8 years the lake above the dam was filled and the slope of the river bed extended upstream from the crest of the dam on a slope of 1:250, or about half that of the original river bed. This raised the river level so much at the hydroelectric plant that it was threatened with flooding, and it was necessary to blast off the top of the dam downstream to prevent it.

Extensive changes of level above dams have been investigated in India in connection with the great irrigation works in the Indus River basin.[29,30,31]

Examples of Class 4

Class 4 profile changes (Figure 1-d) result from the lowering of the temporary base level of the stream and causes effects somewhat similar to those upstream from point C in Class 2. This case often occurs when a reservoir, which is usually held at a constant level, is drawn down. The Salton Sea in California, U.S.A., was at one time filled to an elevation of 40 feet above sea level and the Whitewater River[12 p. 320] built a grade adjusted to this level. The sea has been cut off from the ocean and lowered by evaporation to 250 feet below sea level, and the Whitewater River is slowly adjusting itself to this new base level. The flow in the river is ordinarily very small so that the adjustment is slow; but in the rare large floods, scour proceeds rapidly upstream in a series of cataracts. Another example is the Mojave River which flowed into ancient Lake Manix. This lake drained itself by cutting through a barrier, and the stream is now adjusting itself to the new level. Over a long period of time such changes have taken place in many large rivers.

It is known that the level of the ocean during glacial times rose and fell several times as more or less ice was imprisoned on the earth surface in the form of glaciers. The lowerings reached as much as 325 feet below the present level. During these glacial changes, the beds of all of the streams which flowed in erodible deposits and entered the sea were probably adjusted to the lower level as they are now adjusted to the present level. Recent geological investigation[9] has shown that the Mississippi River was so adjusted.

Examples of Classes 5 and 6

Classes 5 and 6 (Figures 1-e and 1-f) result from the base level moving up or down the stream without a change of elevation. Illustrating Class 5 is the following set of circumstances: A railroad runs up the valley of the Missouri River in the United States and small tributaries of the river pass under the railroad in culverts. When the railroad was built at the point where one of these tributaries entered the river, the river flowed along the side of the valley near the railroad and the culvert was set to conform to the grade established by this situation. The Missouri River shifted to the other side of the valley and the distance from the culvert to base level in the river increased. This caused a raising of the grade of the tributary to such an extent that it was necessary to raise the grade of the railroad where it crossed the tributary. An illustration of Class 6 has occurred in the lower Mississippi Valley.[8] Here the Mississippi River has shifted from the west to the east side of the valley; and streams entering this river from the east, which were adjusted to the former position, have cut down their beds to the altered position of the base level.

The foregoing discussion of the six classes has assumed that the stream

on which the changes occurred was in equilibrium before the change occurred. In applying the reasoning developed to the case of any particular river, it is necessary to know whether or not that stream is in equilibrium. For example, a change in the conditions on a stream in equilibrium which would produce an aggrading profile, might produce in a degrading stream only a slowing down of the rate of degrading. Similarly a change of conditions that would produce degradation in a stream in equilibrium might, in a stream which was aggrading, produce only a slowing down of the aggradation, unless the degrading effect of the change was greater than the present aggradation.

In the foregoing analysis only the vertical movements of the streams have been discussed, but horizontal changes accompany the vertical ones. These changes are also important, but comparatively little study has been given to this phase of the subject. A good start has been made by Leopold and Maddock,[37] who have investigated the shape of the cross-section of streams under various conditions. The writer is engaged in a quantitative study of the form of the plan of streams, such as meandering and braided, but much further study in this field is needed.

CONCLUSIONS

Fluvial morphology is the science of the forms of the earth's surface produced by flowing water. This science is of major importance to the hydraulic engineer, since many of his greatest problems arise because of such forms. Fluvial morphology has been studied most extensively as a part of geomorphology, which is a subdivision of the science of geology. The hydraulic engineer can learn much from the writings of the geomorphologists. Engineers have also contributed to progress in this field.

The concepts of 1) the stages of development of a river proposed by W. M. Davis, 2) of base level, to which streams tend to cut down and 3) of equilibrium in stream channels, will be of considerable assistance to hydraulic engineers in their analysis of plans for stream control.

Many problems arise because of the changes which take place in the profile of streams as the result of the works of man, or sometimes by natural causes. Because of the progressive nature of these changes, and the large number of hydraulic works that have been recently constructed, these problems are likely to be more frequent and important in the future than they have been in the past. In this paper an attempt has been made to classify these changes and to give illustrations of cases where they have occurred. It is believed that a study of this classification and the examples, will aid the hydraulic engineer in working out rational answers to some of his projects.

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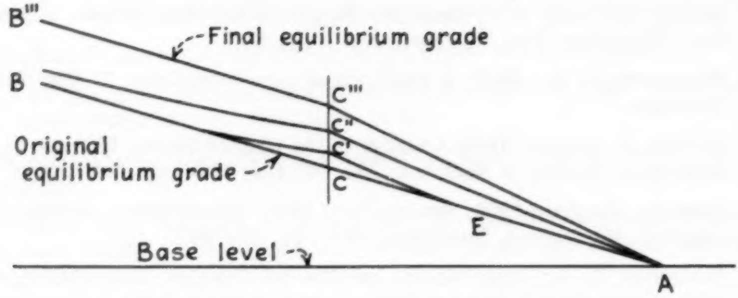
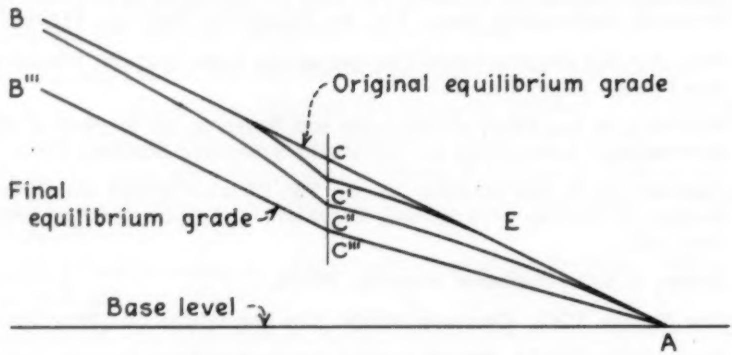


FIGURE 1-a CLASS 1



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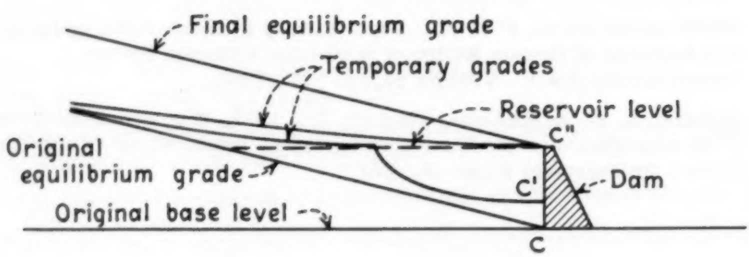

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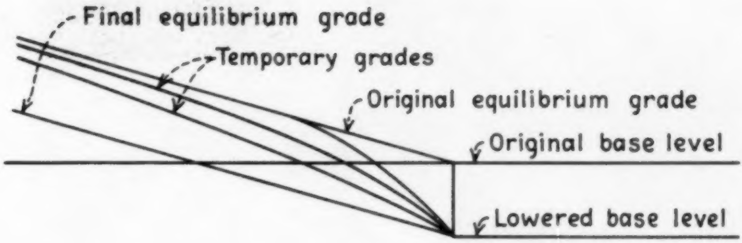

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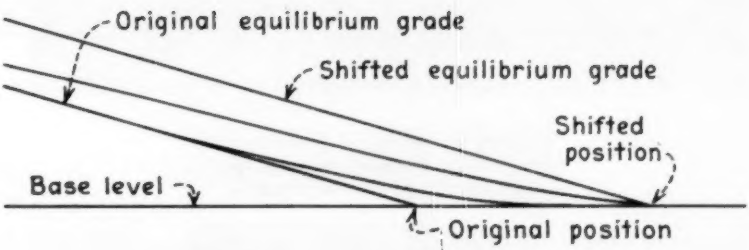

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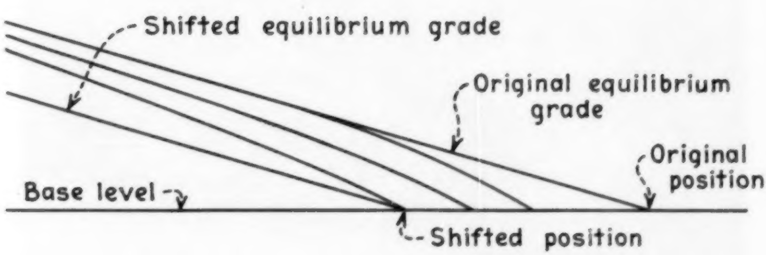

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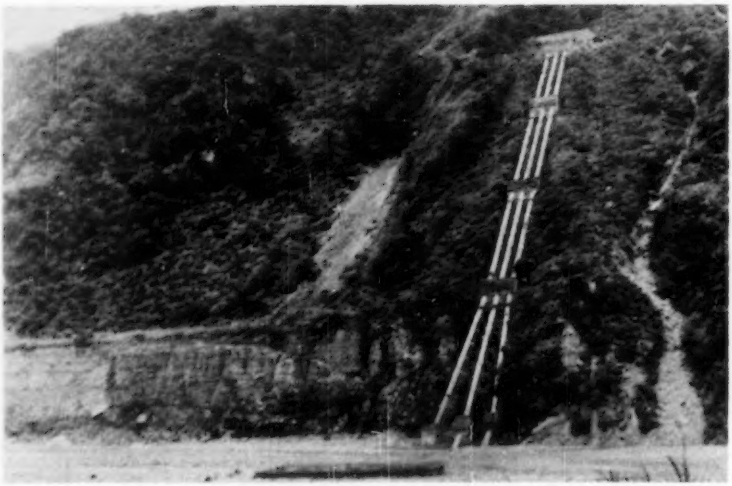

Figure 2. Roof of Powerplant Buried by Rise of Bed of the Mu Kwa River in Formosa

Figure 3. Degradation below Ft. Sumner Dam on Pecos River in New Mexico

Figure 4. Waterfall on Five Mile Creek, Wyoming, Resulting from Grade Reduction Caused by Increase in Discharge

Figure 5. Bed Lowering in Cherry Creek, Denver, Colorado, Caused by Reduction of Sediment Load

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